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Self-consistent modelling of X-point MARFE and divertor detachment

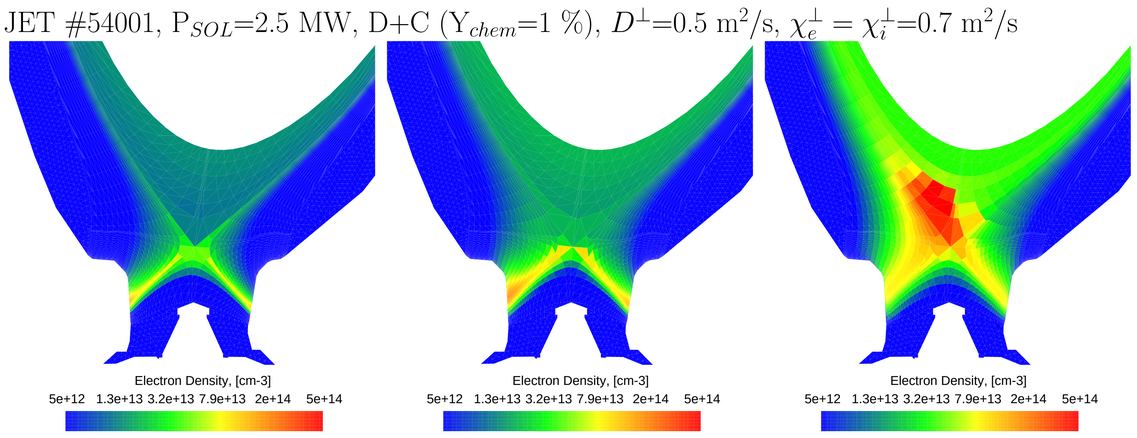
V. Kotov*, D. Reiter, S. Wiesen

Institut für Energie- und Klimaforschung - Plasma Physik, Forschungszentrum Jülich GmbH, EURATOM-Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany
(e-mail:v.kotov@fz-juelich.de)*

MARFEs are radiating regions of high density (n_e >∼10^{20} m^{-3}) and low temperature (T_e ∼<1 eV) plasma seen on the tokamak edge at high discharge densities

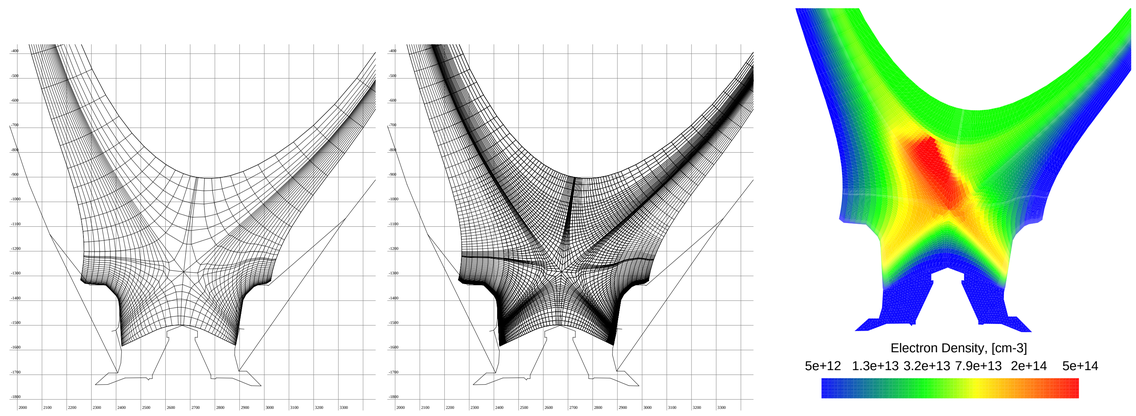
X-point MARFE in the *steady-state* B2-EIRENE simulations

JET #54001, P_{SOL}=2.5 MW, D+C (Y_{chem}=1 %), $D^{\perp}$=0.5 m^2/s, $\chi_e^{\perp} = \chi_i^{\perp}$=0.7 m^2/s



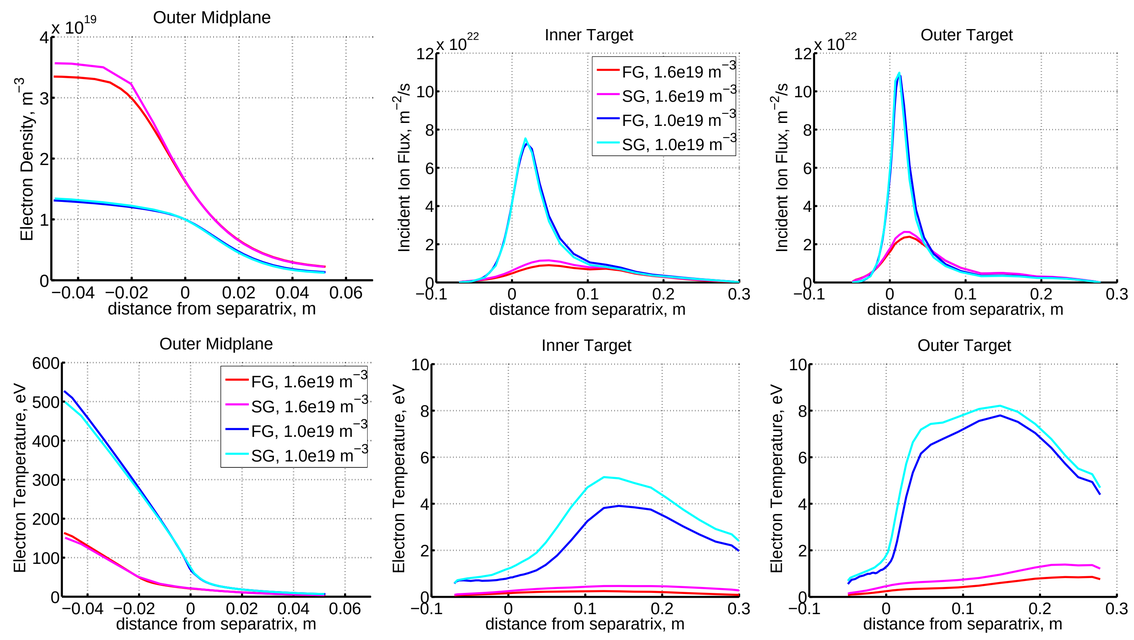
n_e^{mid}=1.0e19 m^{-3} n_e^{mid}=1.24e19 m^{-3} n_e^{mid}=1.62e19 m^{-3}

Verification of the model using High Performance Computing

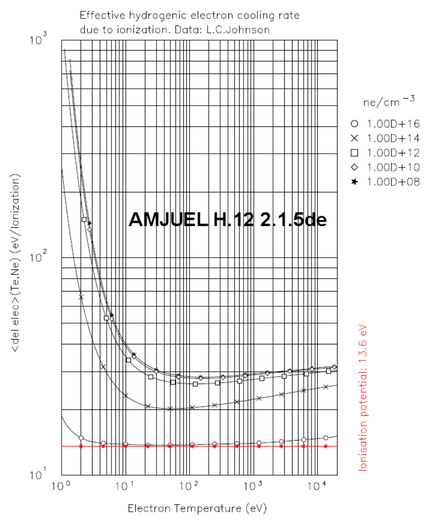


Standard Grid (**SG**), 96×24 Refined Grid (**FG**), 284×42 n_e^{mid}=1.62e19 m^{-3}

Calculations on HPC-FF, 256 processors, ≈4·10^5 neutrals, ≈5·10^6 photons



Stable solution with MARFE only if Ly opacity is taken into account



MARFE is optically thick, absorption/emission [%]

n^e_{mid} 10^{19} m^{-3}	0.5	1.0	1.24	1.62	1.6FG
Ly-α	5.8	41	60	87	91
Ly-β	1.0	9.5	18	62	71

Opacity constrains radiative energy losses per ionization

No artificial feedback control for steady-state solution

Technical criteria of "steady-state"

- (Error in particle balance)/(Γ_{puff} + Γ_{core}) <5 %
- (Error in energy balance)/ P_{SOL} <3 %
- Characteristic decay time $\tau^{-1} = \frac{1}{X}\frac{dX}{dt}$ >1 sec ($\ln X = \tau^{-1} \cdot t + C$) for
  - Average separatrix T_e, T_i, n_e, Z_{eff}
  - Total amount of ions
  - Total diamagnetic energy in electrons and ions

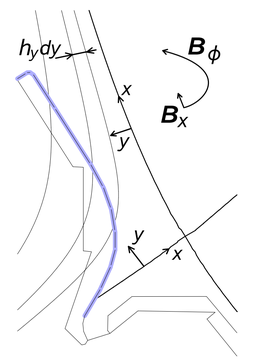
MARFE in the momentum balance

$$\frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left(\frac{\sqrt{g}}{h_x}\frac{B_x}{B}\sum_\alpha m_\alpha n_\alpha \left(u_\alpha^{||}\right)^2\right) = -\frac{1}{h_x}\frac{B_x}{B}\frac{\partial P}{\partial x} + S^{mom}_{neut} + S^{mom}_{other}$$

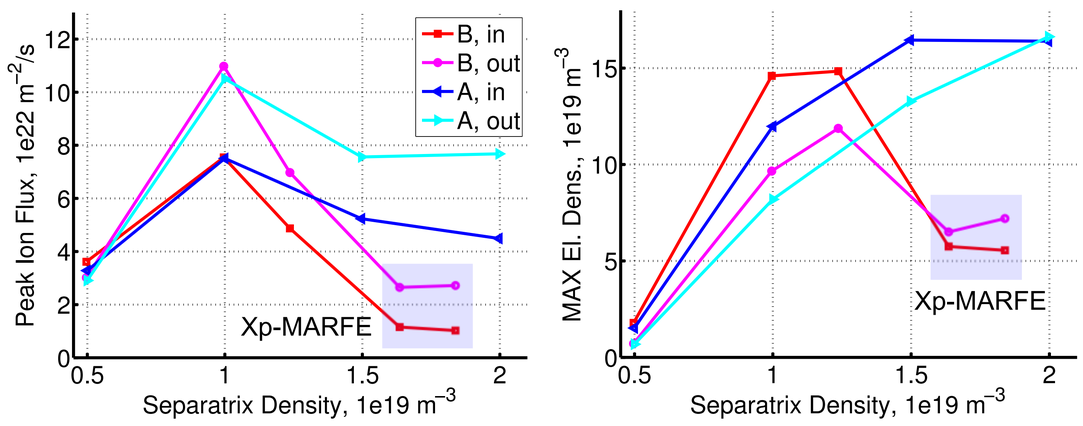
$$\Pi_u - \Pi_x = \Delta\Pi_{neut} + \Delta\Pi_{other} + \Delta\Pi_{geom}$$

$$\Pi = \frac{1}{s_t}\frac{B_x}{B}\frac{\sqrt{g}}{h_x}\left(P + \sum_\alpha m_\alpha n_\alpha \left(u_\alpha^{||}\right)^2\right) \qquad s_t = \frac{B_x}{B}\frac{\sqrt{g}}{h_x}$$

$$\Delta\Pi_{neut} = \frac{1}{s_t}\int_u^x S^{mom}_{neut}\sqrt{g}dx; \quad \Delta\Pi_{geom} = \frac{1}{s_t}\int_u^x \frac{P}{\sqrt{g}}\frac{\partial}{\partial x}\left(\frac{\sqrt{g}B_x}{h_x B}\right)\sqrt{g}dx$$

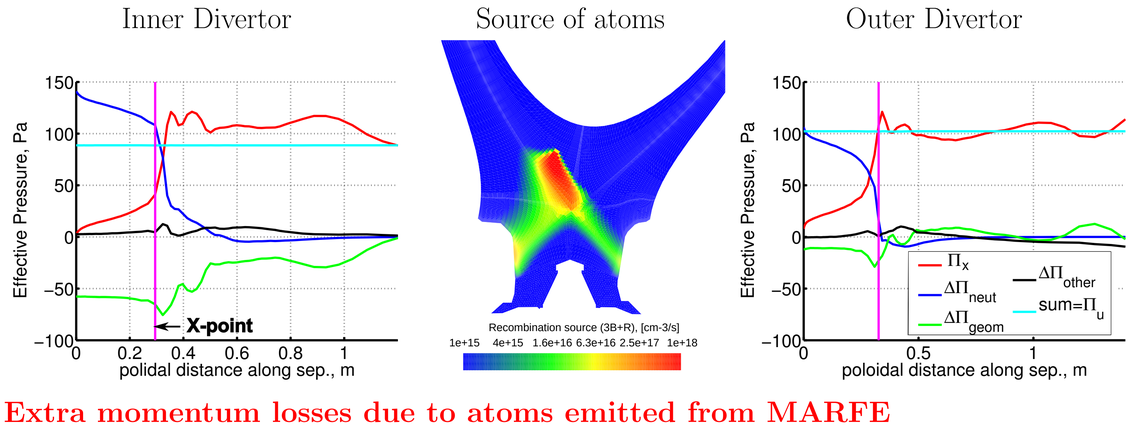


"Deeper" detachment after formation of MARFE



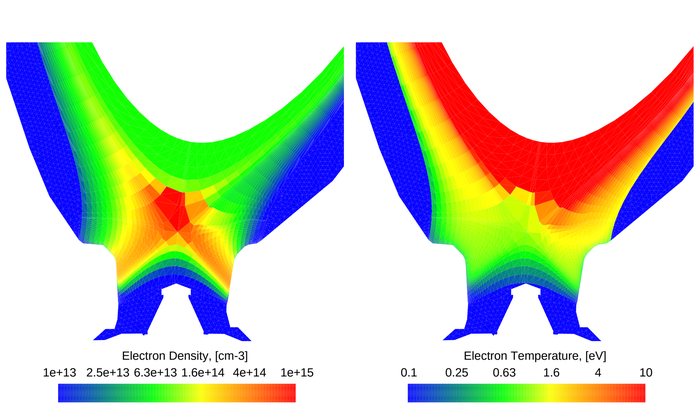
Model B=Model A + NNC + MAR + *transport of Ly photons and photo-excitation*

Inner Divertor Source of atoms Outer Divertor

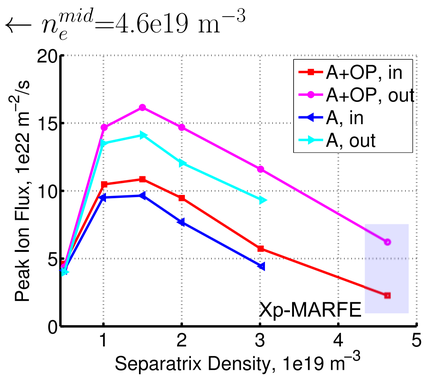


Extra momentum losses due to atoms emitted from MARFE

Similar observations with pure D plasma

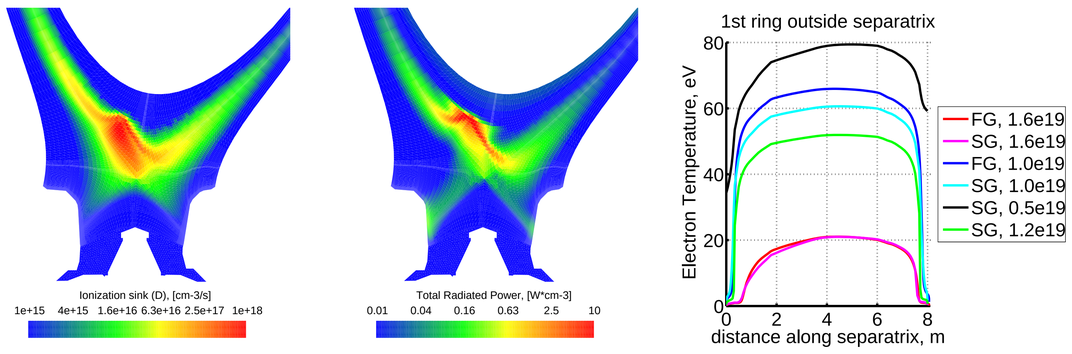


← n_e^{mid}=4.6e19 m^{-3}



A+OP=Model A + Ly opacity

Reduction of upstream temperature (thus, pressure)



n_e^{mid}=1.6e19 m^{-3} f_{rad}=81 % (D: 28 %, C: 72 %) same drop for T_i

Ionization source ⇒ enhanced convective energy flux ⇒ reduced parallel gradient

Can this effect be checked experimentally ???